Acceleration Scenarios

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Acceleration for a High Energy Muon Collider

- Start with beam with momentum 186 MeV/c
- Large longitudinal emittance
  - 500 GeV collider: 0.024 eV-s
  - 10 TeV collider: 0.021 eV-s
  - 100 TeV collider: 0.047 eV-s
- Accelerate to desired energy
- Minimize decays (cost: longer run)
- Minimize system costs

Initial Stage: Linac

- Large longitudinal emittance
  - Large relative energy spread at low energies
  - Arcs difficult
- Large losses at low energies: don't waste time in arcs
- Linac relatively short
- Design based on matching beam to RF bucket in adiabatic approximation
  - Bucket area determined by emittance: adjust phase to fill bucket
  - Switch frequency to get higher gradient
    - Higher frequency, larger gradient
    - Higher frequency, further off crest
  - Adiabatic approximation wrong with these gradients: probably good initial guess

10 TeV:

Energy GeV	Freq MHz	Len. m	Loss %	P_{peak} MW	P_{avg} MW
0.186→0.61	50	123	5.7	1076	9.0
0.61→1.9	200	194	2.7	2238	5.3
1.9→4.0	800	179	1.1	3606	2.0

100 TeV:

Energy GeV	Freq MHz	Len. m	Loss %	P_{peak} MW	P_{avg} MW
0.186→0.59	25	162	7.5	955	7.2
0.59→1.8	100	256	3.9	2045	4.3
1.8→4.0	400	260	1.6	3685	1.8

- Low frequency RF required
  - Large cavities
  - RF sources difficult (low frequency)
  - Large power requirements
  - Small efficiency (power to beam: few kW)
  - 25 MHz probably prohibitive: need to reduce longitudinal emittance
- Split large longitudinal emittance bunch into several bunches with smaller longitudinal emittance
  - Use higher frequency RF
  - Later arcs become simpler
  - Improve RF efficiency

Recirculating Linacs

- Go through same linac several times
- Increase efficiency (average power): more turns better
- Muons can be bent
- Size determined by largest energy
  - Minimize decays: smaller recirculator for lower energies
  - Lower energies, low frequency RF required: switch to allow higher RF frequency
    - ⋆ Better gradients
    - ⋆ Easier to get RF power
    - ⋆ Better efficiency
- Different types of arcs

- Multiple arc
  - Each pass, different arc
  - Have full control of map through arc
    - Path length: hit RF at right phase
    - Momentum compaction: longitudinal dynamics
    - Match correctly into straights
    - Chromaticity
  - Switchyard difficult
    - Fast at lower energies
    - Large beam size
    - Sufficient turn-to-turn energy jump: can do passively
  - Low energies: relative energy spread large
    - May need factor of 2 in energy in one arc
  - Many turns: lots of arcs

- Fast ramping magnets
  - Like synchrotron
  - Use SC to minimize decays, but can't ramp SC fast enough
  - Lower energy: circumference short, insufficient time to ramp NC
  - To keep high average fields: hybrid scheme
    - Fixed field SC magnets
    - Interleave NC magnets, ramped from $-$max to max.
  - Same arc for multiple passes
    - Lose turn-by-turn control of map
      - Not synchronized with RF phase
      - Other dynamics can't be controlled
      - Fix with other ramped magnets
    - May still have energy acceptance problems

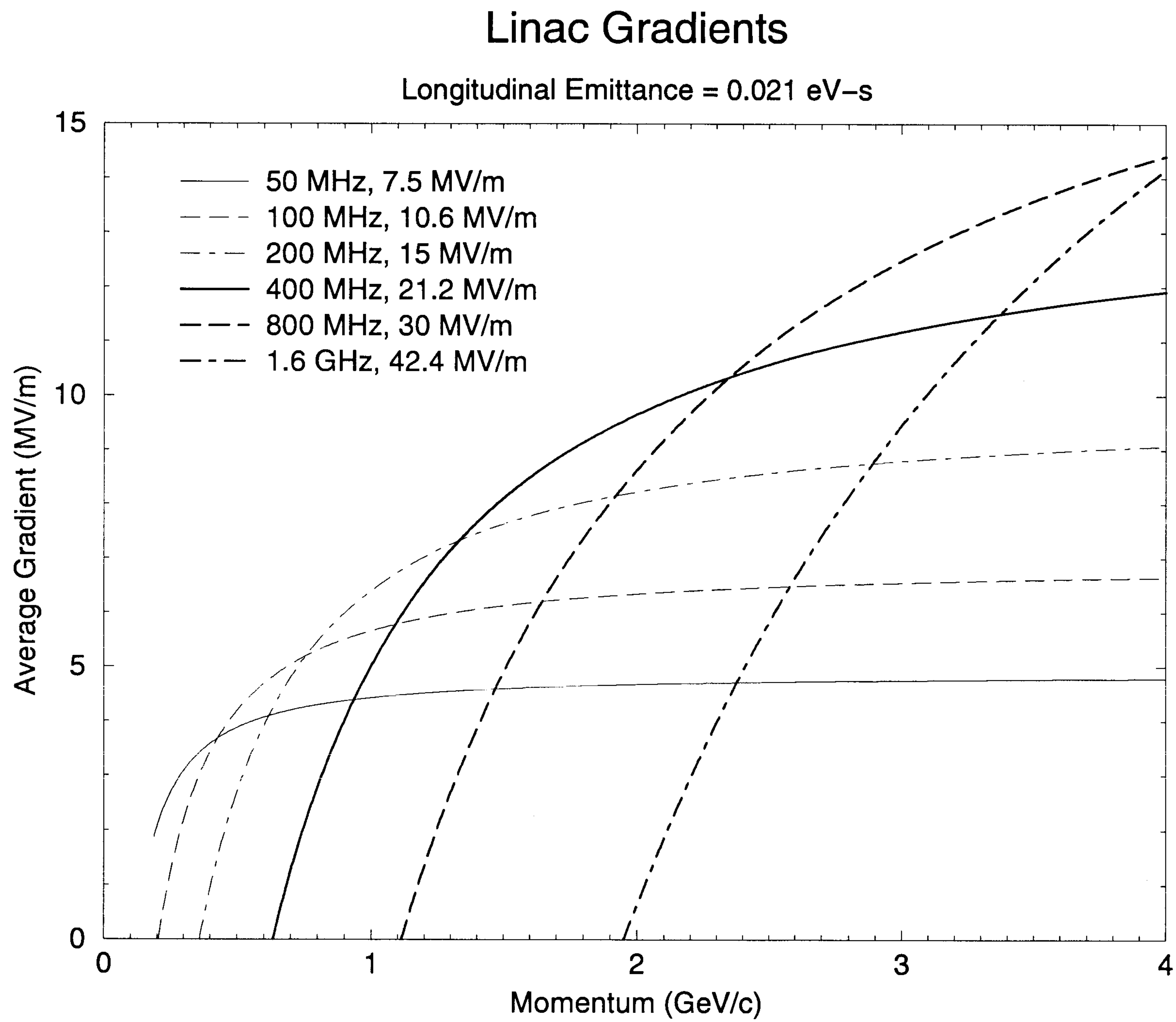
- FFAG
  - Fixed-field magnets
  - Accept large range of energies in one arc
    - As much as factor of 4 or more
    - Large fraction of quadrupoles
    - Arc length longer: average bend field smaller
  - Only one arc
    - Can't control map turn-by-turn
      - Can't synchronize with RF phase
      - Longitudinal dynamics different for each pass
      - Only matched into straight for one energy
      - Chromaticity uncorrected
      - Potentially fix with ramped NC magnets: high energy only
  - Accepts large energy spread in beam for free
    - In multiple arc scheme, some low energy arcs require this type for only one turn
  - Potentially combine with fast ramping scheme: get extra degree of freedom from ability to ramp?

- Example recirculators: 10 TeV collider
  - 4-16 GeV recirculator
    - 800 MHz RF (lower frequency: larger momentum compaction needed, but better energy spread)
    - 5 turns: multiple arcs which don't need switchyard
    - $\alpha = .013 \rightarrow .052$, $\beta = 0.8 \rightarrow 1.6$ m (can make easier by reducing synchrotron tune, but energy spread increases)
    - $\sigma_\tau = 80$ ps, $\sigma_E = 300$ MeV: first arc must accept factor of 2 in energy!
    - Decay loss: 1.7%
    - Max efficiency: 18.5%
    - Min peak power (matched): 924 MW
    - 3 μs circulation time: no time to ramp
  - 0.5-1.6 TeV recirculator
    - 800 MHz
    - 50 turns
    - $\alpha = 0.0039 \rightarrow 0.0124$, $\beta = 44 \rightarrow 79$ m
    - $\sigma_\tau = 39$ ps, $\sigma_E = 609$ MeV
    - Decay loss: 4.65%
    - Max efficiency: 71.7%
    - Min peak power (matched): 281 MW
    - Can go to many more turns: decays worse, efficiency, peak power better.
    - 0.94 ms circulation time: time to ramp

- Dynamic adjustment of path length
  - Single-arc recirculators:
    - Different path lengths for each energy
    - Must correct to get correct RF phase
  - Correct errors
    - RF energy/phase error
    - Beam current error (beam loading, energy changes)
    - Bad timing of bunch
  - Methods
    - Pump in RF
      - High peak power
      - Better at high energies (longer time)
    - Vary frequency to vary phase
      - Saturate ferrites
      - Photodiodes
    - Ramping magnets
      - Only at higher energies with more time
  - Cannot correct momentum compaction (slope of RF) using these methods
    - Want α/E constant

Instabilities

- Higher frequency RF gives larger wakefields
- Induce synchrotron oscillations to prevent linac instabilities
  - 0.15 per linac-arc pair is maximum tune
    - Racetrack design gives 0.3
    - Can go to many-sided design to improve, but added overhead
  - Potential head-tail instabilities: chromaticity not always corrected
- Transients may dominate behavior
- Power advantage to lower gradients, but instabilities worse



Linac Gradients
Longitudinal Emittance = 0.021 eV–s
50 MHz, 7.5 MV/m
100 MHz, 10.6 MV/m
200 MHz, 15 MV/m
400 MHz, 21.2 MV/m
800 MHz, 30 MV/m
1.6 GHz, 42.4 MV/m
Average Gradient (MV/m)
Momentum (GeV/c)
0
5
10
15
0
1
2
3
4

Linac Gradients

Longitudinal Emittance = 0.047 eV–s